



Orion EM-1 Internal Environment Characterization: The Matroska AstroRad Radiation Experiment

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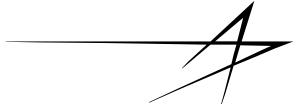
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⁸European Space Agency (ESA) Astronaut Center (EAC), Köln, Germany



R. Gaza for the MARE team

Presentation Outline



2019 ASEC, Los Angeles, CA

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- Orion
- AstroRad
- ISS Matroshka
- **Matroshka AstroRad Radiation Experiment (MARE) on Exploration Mission 1**



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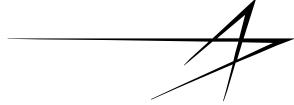
Orion MPCV

- The Orion Multipurpose Crew Vehicle (MPCV) is NASA's next generation spacecraft for human exploration of the solar system
- Exploration Flight Test 1 (EFT-1) successfully executed December 2014
 - High eccentricity high altitude orbit to 3600 mi
- EM-1 (Exploration Mission 1) is scheduled for 2020
 - 21-42 days mission to Cis-lunar space
- EM-2 is scheduled for 2022
 - First crewed flight
- First Gateway element also scheduled for 2022
 - Power and Propulsion Element PPE
- EM-3 is scheduled for 2024
 - First crewed mission to the lunar surface





Orion Ionizing Radiation



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- **Orion spacecraft design requirements address both electronic systems (e.g., avionics) and crew protection**
 - First NASA human spacecraft to implement an Ionizing Radiation Control Plan (IRCP)
 - Systematic decomposition of SRD high level requirement “Orion shall meet its functional, performance, and reliability requirements during and after exposure to the mission radiation environment”
 - First NASA spacecraft on which Crew radiation protection is levied as a design driving requirement
 - CxP-70024 Constellation Program Human Systems Integration Requirements
 - Spacecraft design “shall provide radiation protection consistent with ALARA and not to exceed crew exposure of $E = 150 \text{ mSv}$ for design reference environment”
 - SLS-SPEC-159 Cross-Program Design Specification for Natural Environments
 - Aug 1972 Solar Particle Event SPE (King parameterization)
- **Evolution of radiation protection requirements beyond Orion**
 - Townsend et al., Life Sciences in Space Research 17 (2018) 32–39
 - BFO limit of 250 mGy-equivalent for the design SPE chosen as Oct 1989
 - ALARA, storm shelter availability within 30 min of event onset



Orion Requirement Verification

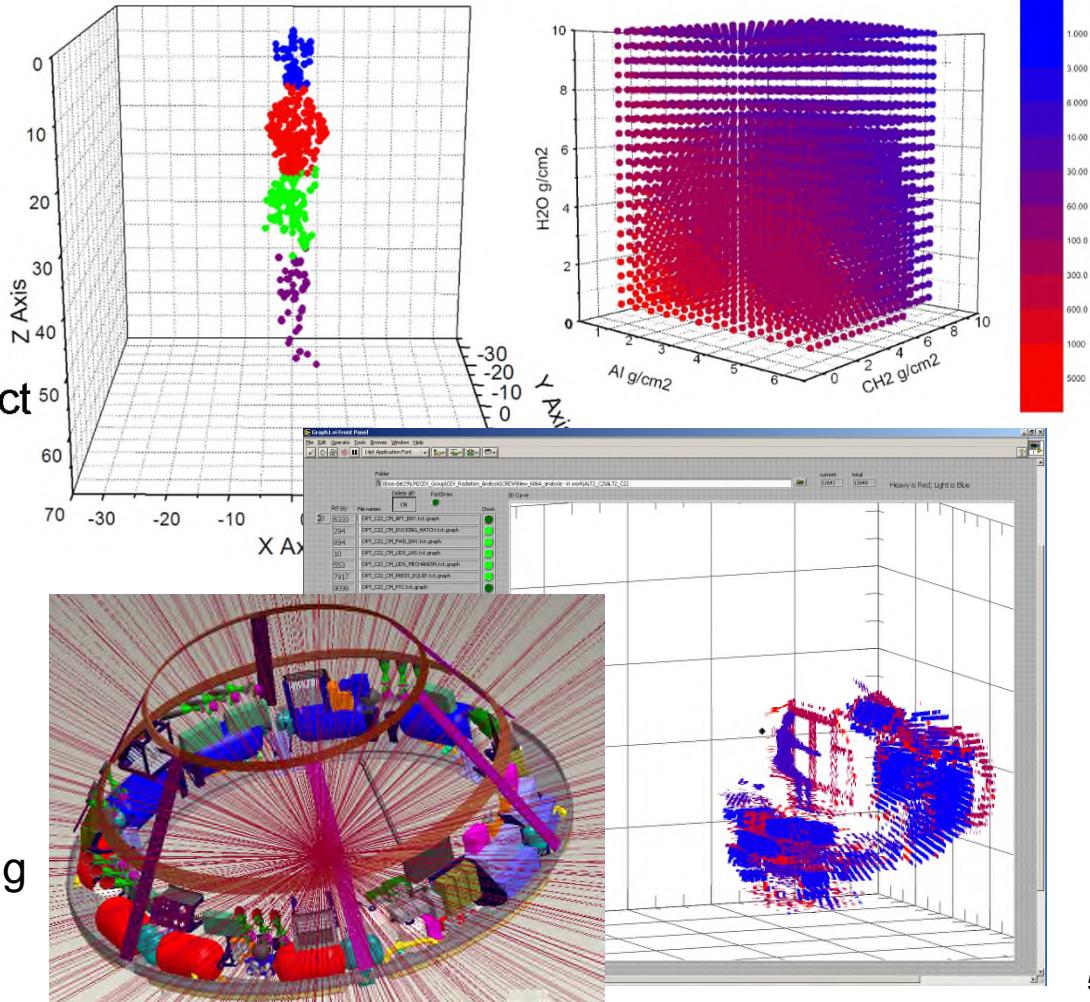
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• Crew Radiation Analysis

- Manufacturing quality Orion CAD model
 - 20,000 parts & assemblies, 100 GB
 - Mass/density and material properties
- Vehicle shielding by ray tracing
 - 4 origin points/crew member, 10k directions
- Body self-shielding from anatomically correct human models (~600 organ points)
- Ray-by-ray total converted to 3-material equivalents (Al, HDPE, H₂O)
- Point dose equivalent calculations by deterministic transport software HZETRN
 - Definition of design reference environment
- Integrated to obtain organ dose equivalent
- Effective dose calculated w/ tissue weighting factors per NCRP Report 132 (2000)





Cabin Configuration Optimization

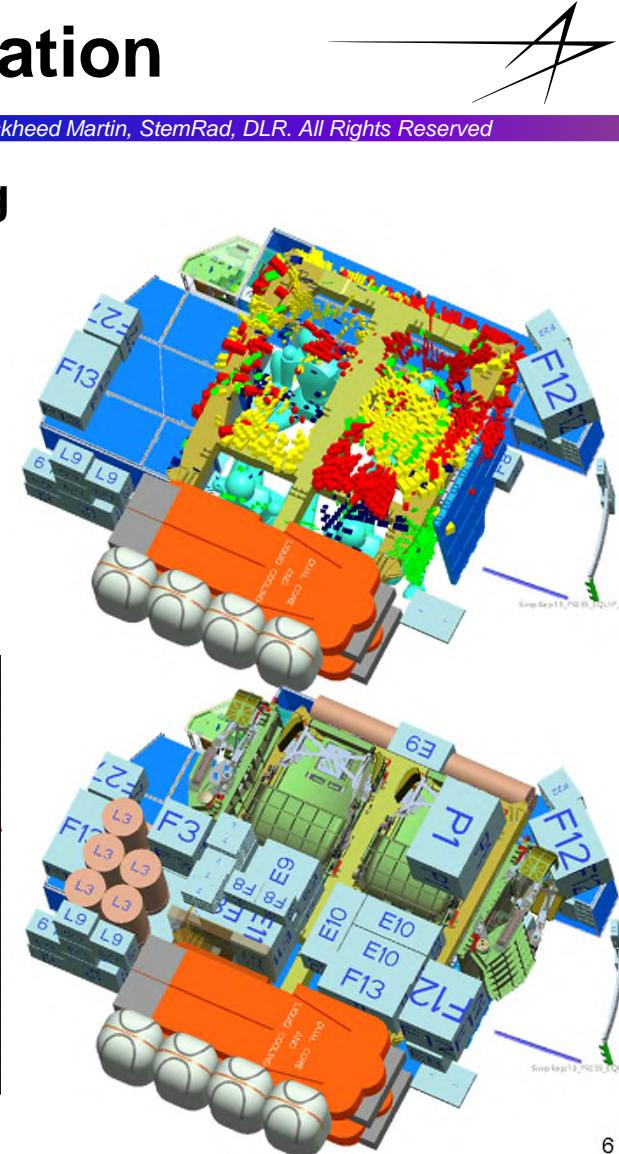
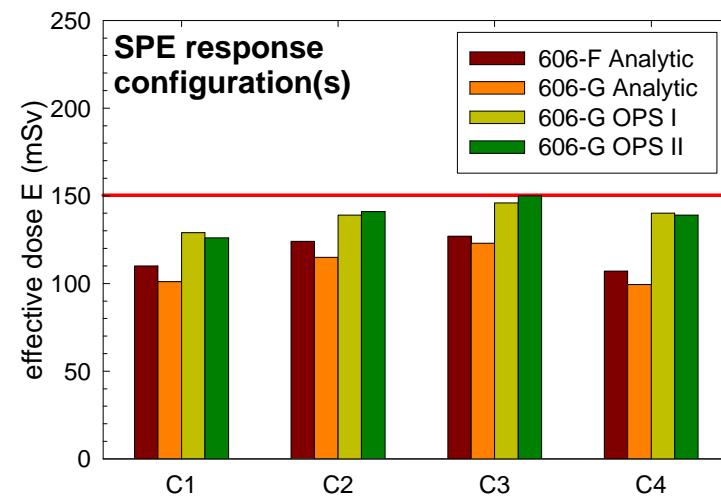
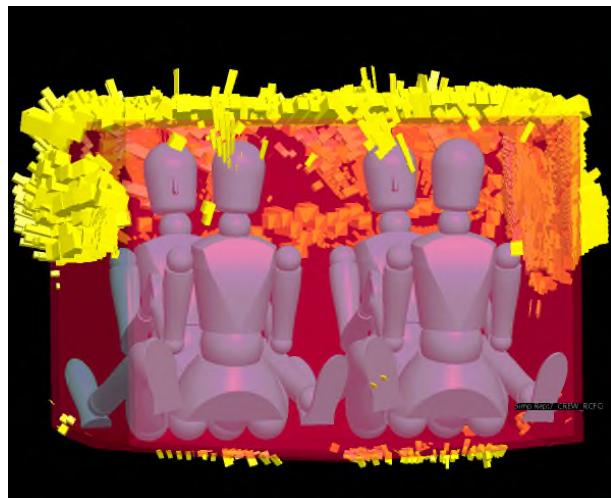
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- Optimization of cabin components locations in lieu of flying dedicated shielding

- Quasi-exponential decay of radiation exposure w/ shielding areal density
- Consistent with ALARA
- Large number of variables renders closed solution difficult
- Semi-analytical method example: visualization of additional shielding location required to achieve predefined target shielding thickness endpoint





Radiation Vest for Astronauts: AstroRad

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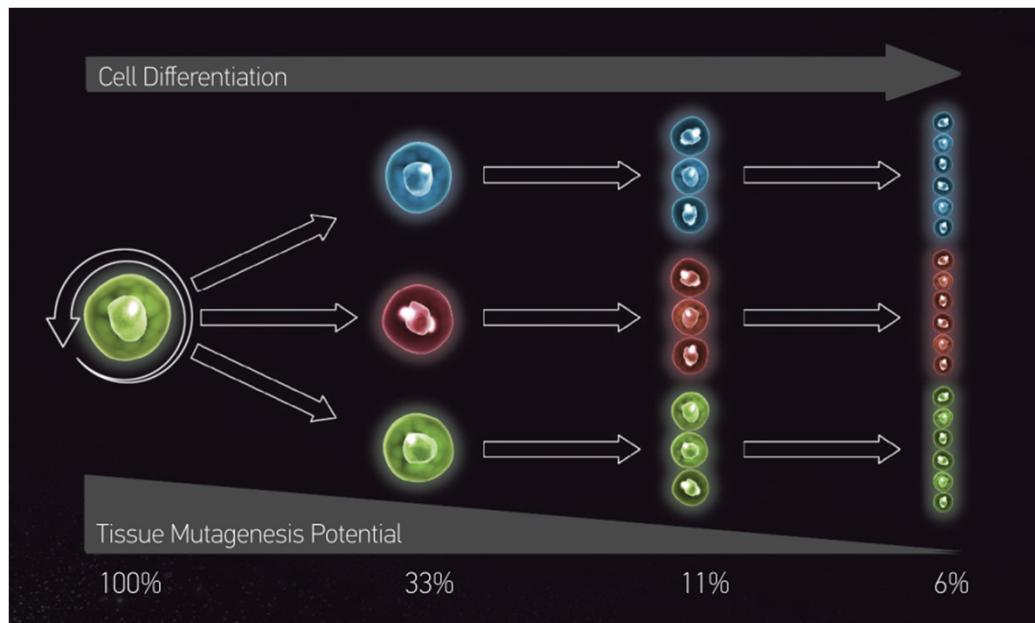
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- **Collaboration between Lockheed Martin Space and StemRad Israel**

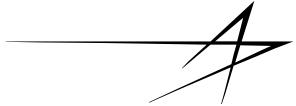
- Portable radiation protection for astronauts
- Provides preferential protection to stem cell rich organs and tissues
- Designed for flexibility and ergonomics
- Ergonomic evaluation aboard the International Space Station pending (launch on SpX-18 July 2019)





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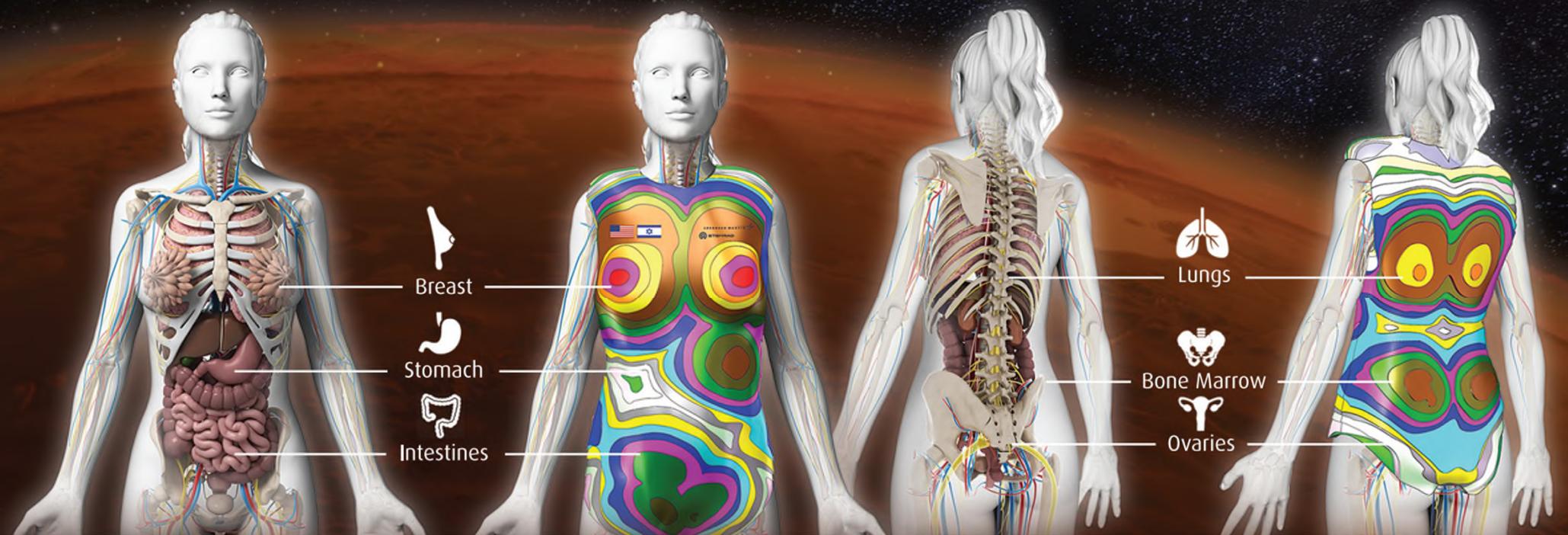
AstroRad



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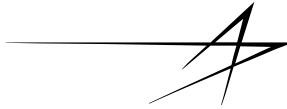
Proprietary Smart Shielding that Focuses Protection on the most Vulnerable Organs:





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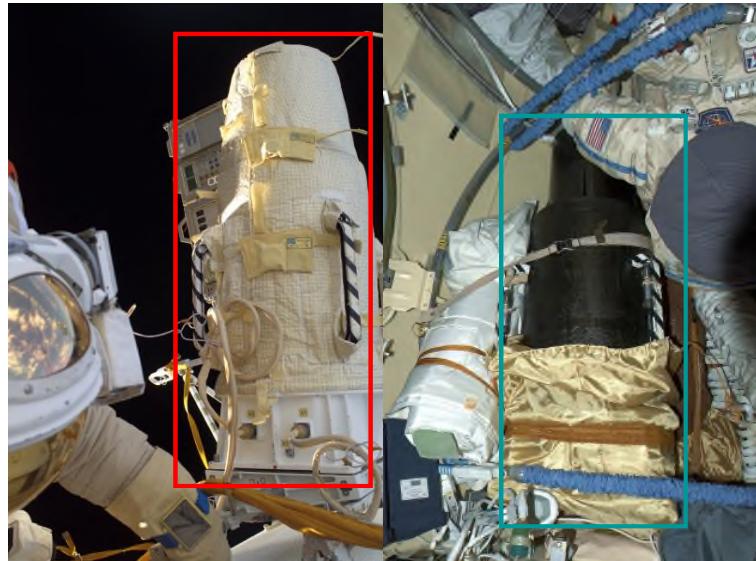
ISS Matroshka



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- Series of radiation measurements in radiation therapy phantoms on ISS
 - Body internal dose mapping using radiation detectors on the surface of, and inside radiotherapy phantoms. Both extra- and intra-vehicular.



MTR-1 539 days
(2004–05)



MTR-2A 337 days
(2006)



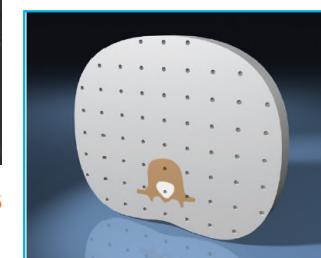
MTR-2B 518 days
(2007–09)



MTR-2 KIBO 310 days
(2010–11)



http://www.cirsinc.com/file/Products/701_706/701_20706%20ATOM%20PB%2020050418.pdf





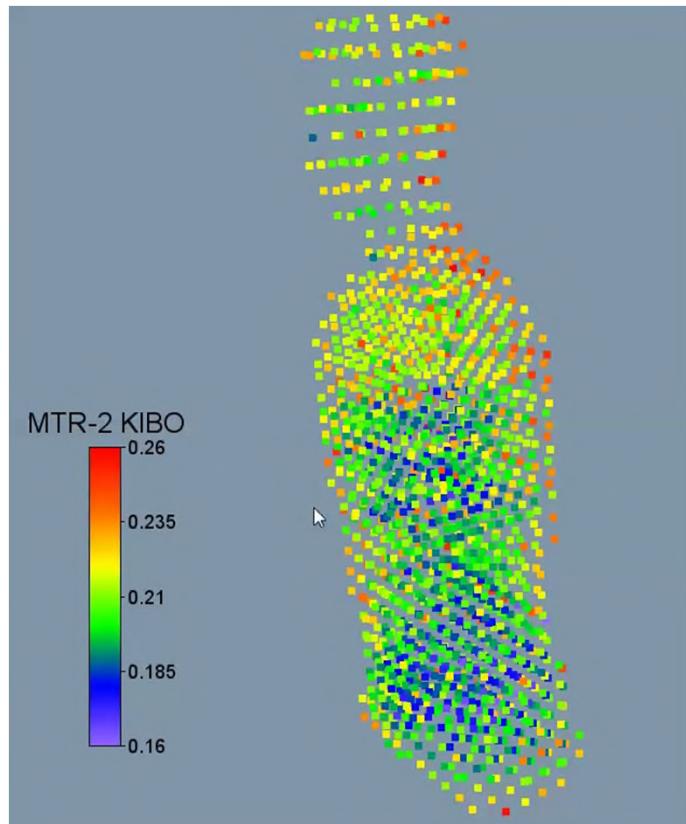
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ISS Matroska



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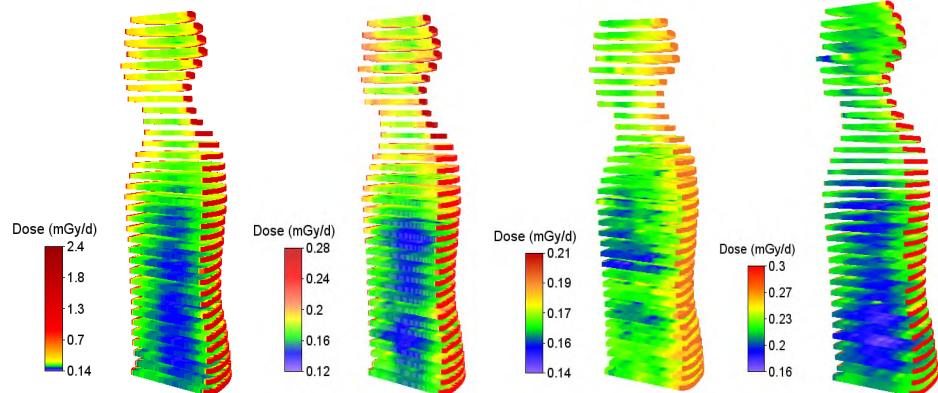


MTR-1
(2004-05)

MTR-2A
(2006)

MTR-2B
(2007-09)

MTR-2 KIBO
(2010-11)



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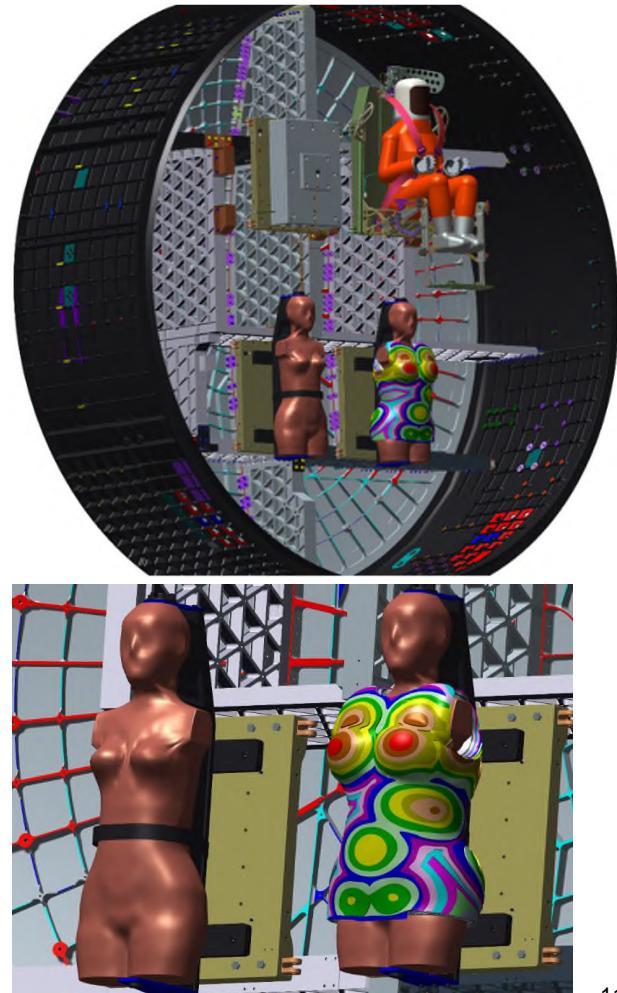
Matroska AstroRad Radiation Experiment (MARE)

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- Lockheed Martin invited feedback as part of Orion radiation protection efforts
- Israel Space Agency (ISA) and the German Aerospace Center (DLR) proposed MARE as an international science payload
- NASA approved the proposal in May 2017 and manifested it aboard the EM-1 flight.
- MARE description
 - Two tissue-equivalent radiation phantoms inside the Orion cabin
 - Fitted with active and passive radiation detectors
 - One phantom fitted with the StemRad-manufactured AstroRad vest
- MARE is managed by DLR and ISA, with NASA as a co-PI
 - Lockheed Martin personnel co-located with Orion support development of MARE science objectives and efficient payload integration aboard the Orion vehicle





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MARE: CIRS Phantoms

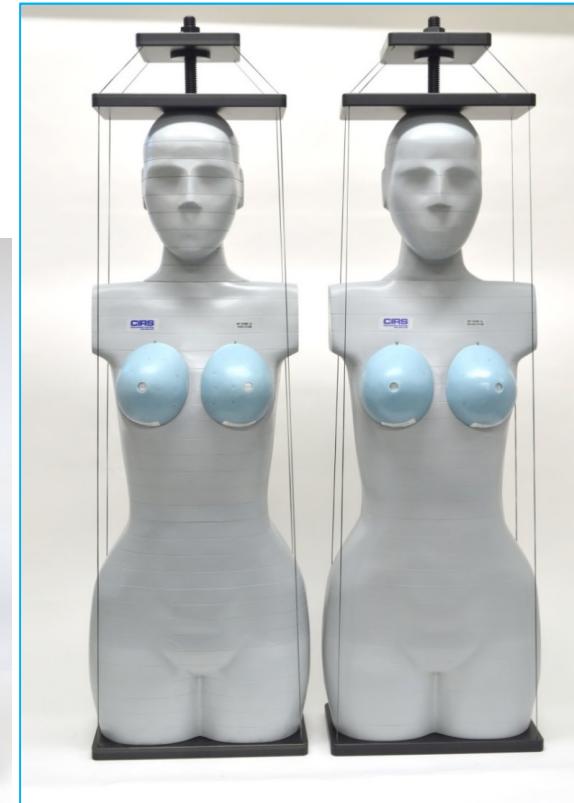
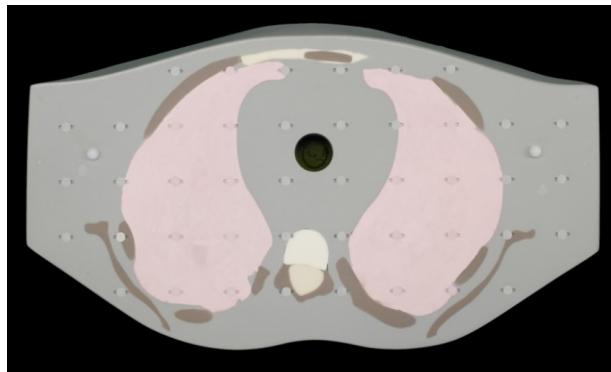


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- **ATOM® 702 Female model**

- Zohar 35.88 kg / Helga 35.99 kg
- Tissue equivalent material, Artificial bone
- 38 slices with TLD/OSLD holes (3 cm custom grid)



<http://www.cirsinc.com/products/modality/33/atom-dosimetry-verification-phantoms>





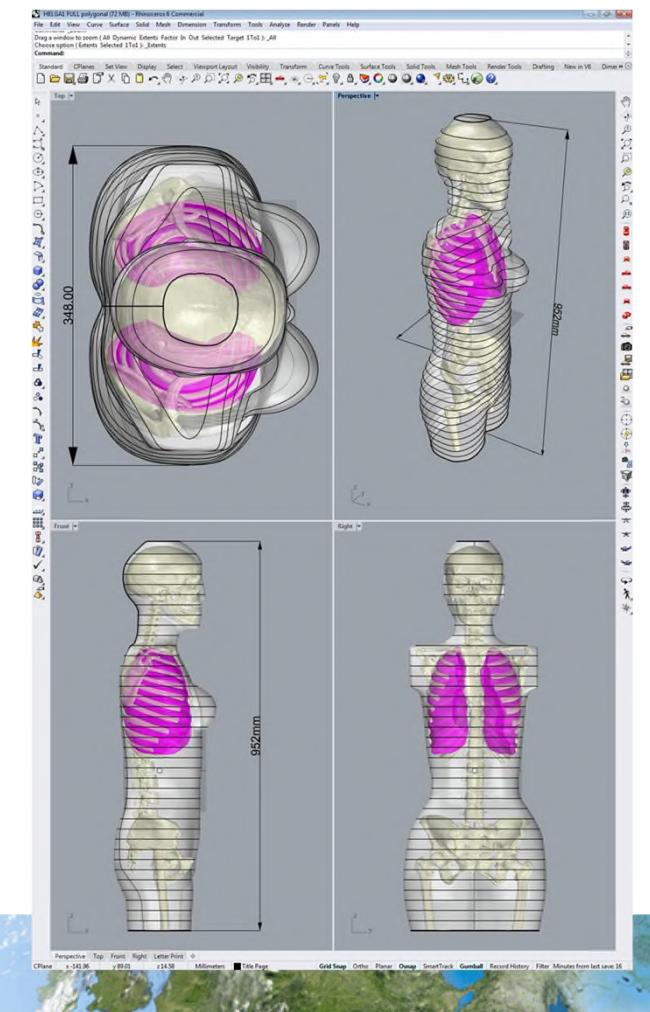
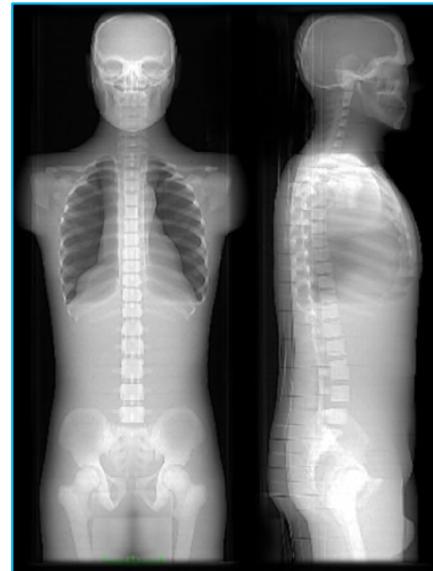
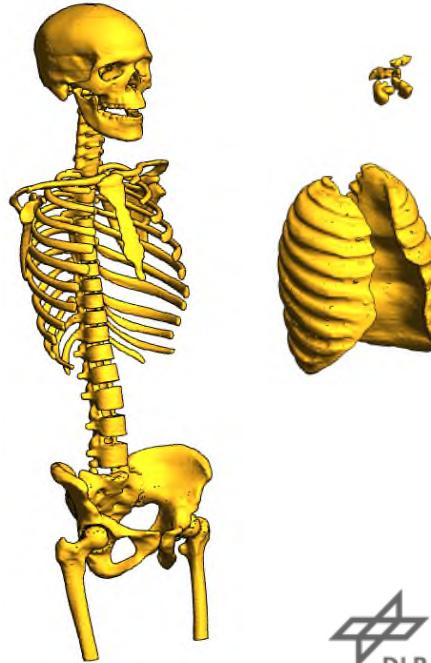
MARE: CIRS Phantoms Internal

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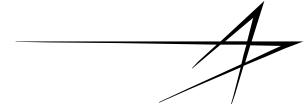
- CT scan performed on each phantom
- CT scan data are used to generate CAD models
- CAD models are used for AstroRad vest customization and radiation analysis





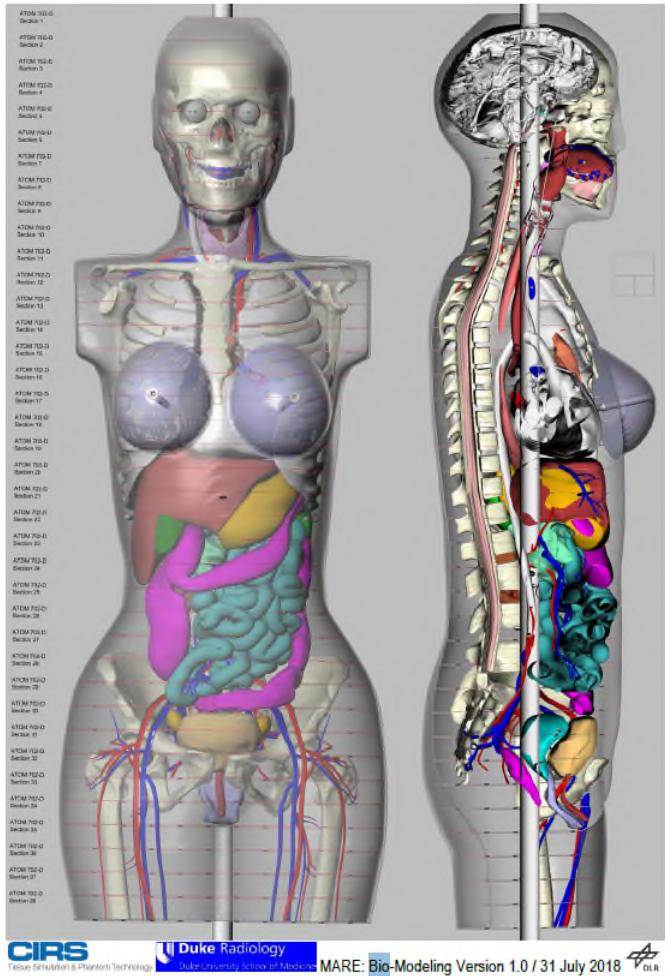
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Bio-modeling

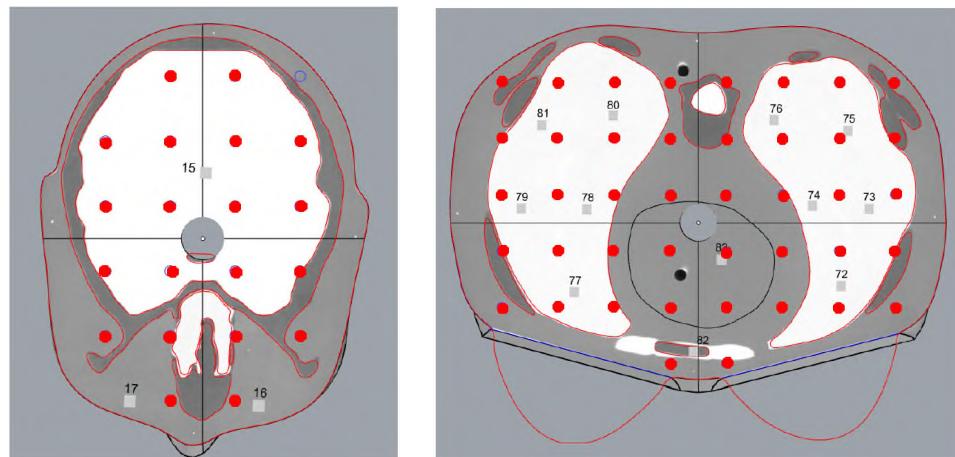


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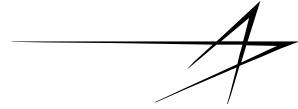


- **Radiation phantom materials**
 - Soft tissue, bone, lung, brain, and breast (and void)
- **CAD Bio-modeling**
 - Courtesy of W. Paul Segars, Ph.D., Duke University School of Medicine
 - Outlines organ shapes within the average soft tissue
 - Associates TLD grid locations with specific organs, allowing for organ dose calculations (analytic prediction & measurements)





Internal Dose Mapping



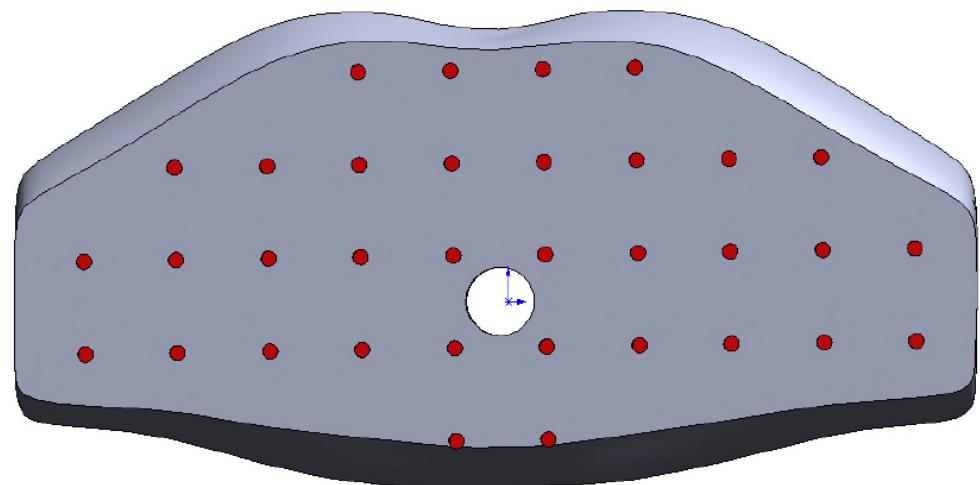
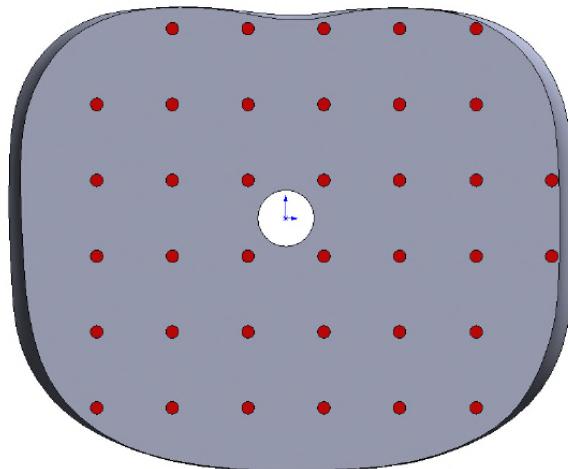
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- **Passive dosimeters internal to the phantoms**

- 3 cm x 3 cm grid
- 6000 TLDs provided by DLR (750 measurement points/phantom, 4 TLDs/measurement point)
- 2000-3000 TLDs & OSLDs provided by NASA JSC (1000-1500 /phantom)



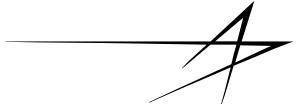


Helga TLD Positions

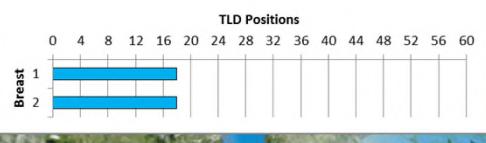
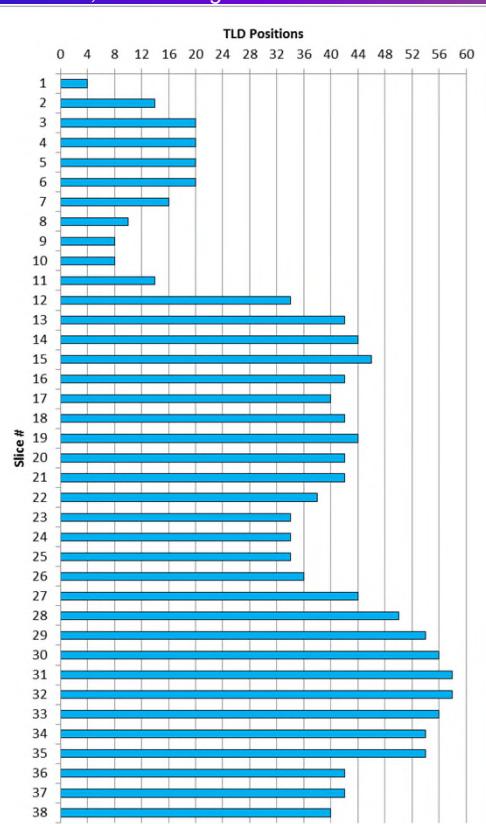
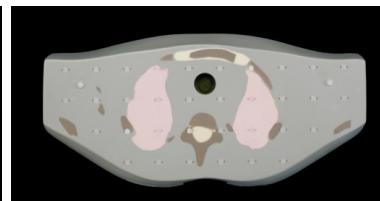
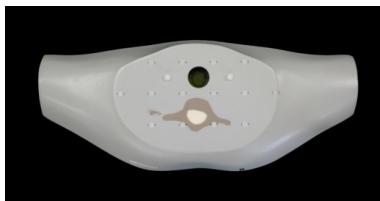
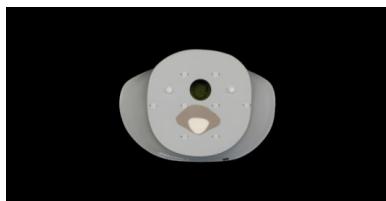
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Helga: 1392, Zohar: 1383 (DLR: 6000 TLDs, NASA: 2-3000 TLDs/OSLDs)





Location Radiation Detectors

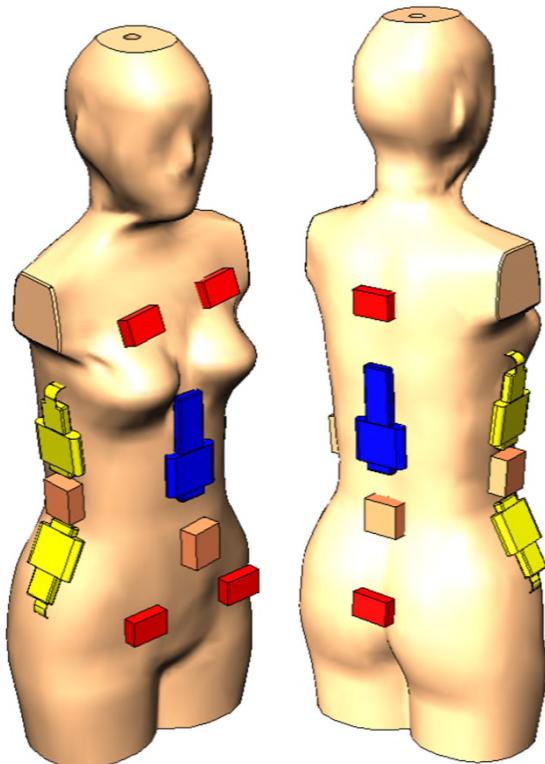


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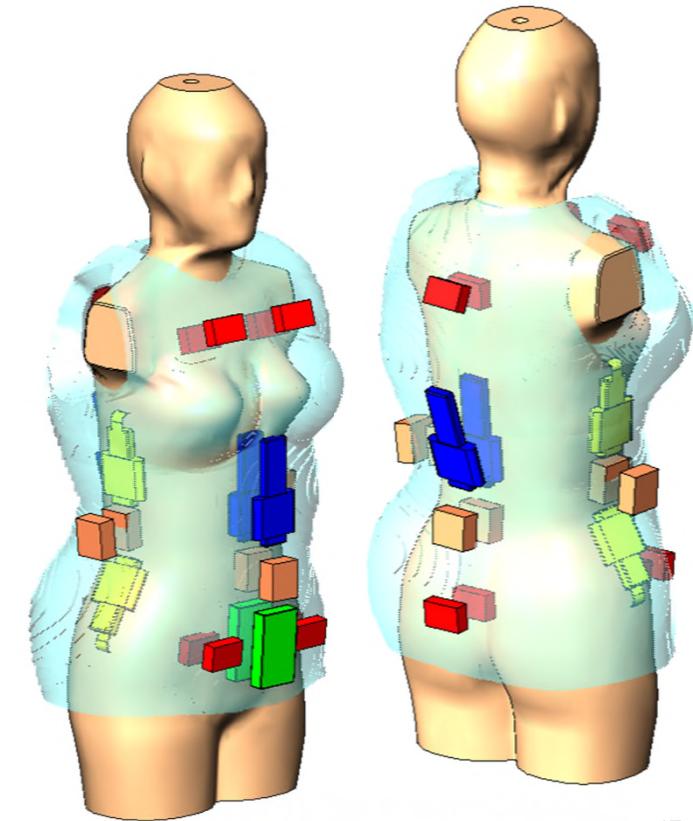
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- Active detectors for surface (skin) and organ location measurements
- DOSIS Passive Dosimeter Packages (PDPs) for surface (skin) measurements
- PDPs provided by DLR for organ measurements (TLD + CR-39)



# Helga	Detector	Org	# Avis
2	M-42 Compact	DLR	4
5	M-42 Split	DLR	5
6	CPAD	NASA	12
1	EAD-MU-O	ESA	2
4	DOSIS PDP	DLR	8
5	DLR PDP	DLR	5





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DLR M42



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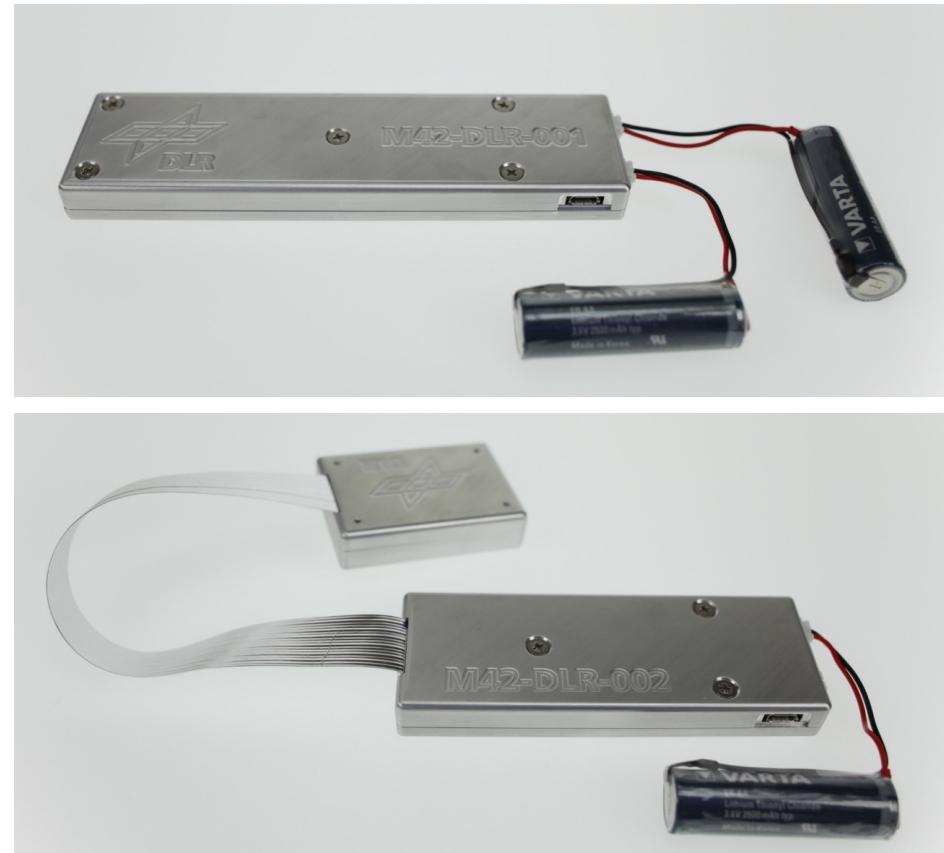
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• Silicon Detector

- 1 cm² area, 300 µm thickness
- Energy range 0.06-20 MeV (Si), 1024 channels
- Autonomous operation
- Launch detection (accelerometer)
- Two versions “Split” and “Compact”

Device	Dimensions	Mass (g)
M-42_C	142 x 38 x 13 mm ³	108
M-42_C (batteries)	Diam. 14.55 mm Height 50.3 mm	2 x 18
M-42_C (battery housing)	72.5 x 54 x 13 mm ³	40
M-42_C (total)		184

Device	Dimensions	Mass (g)
M-42_S	DH: 54 x 38 x 13 mm ³ EB: 106 x 38 x 13 mm ³	120
M-42_S (batteries)	Diam. 14.55 mm Height 50.3 mm	2 x 18
M-42_S (battery housing)	72.5 x 54 x 13 mm ³	40
M-42_S (total)		196



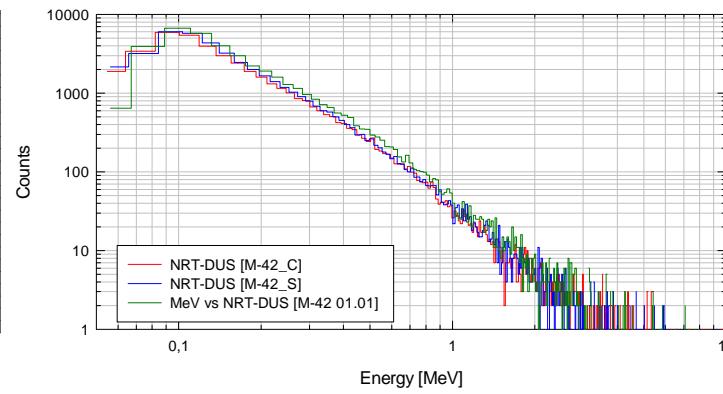
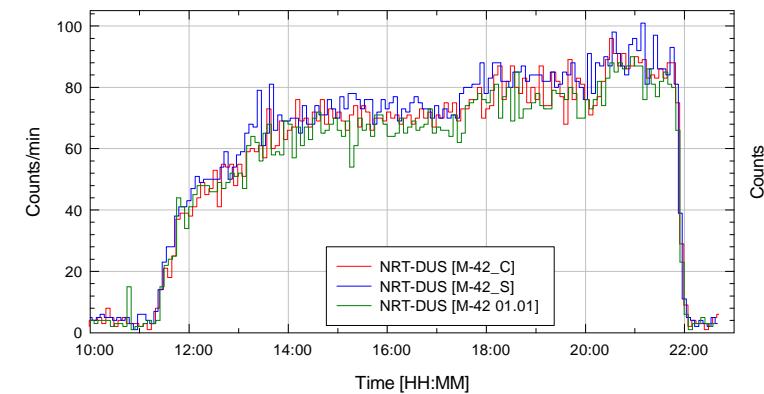
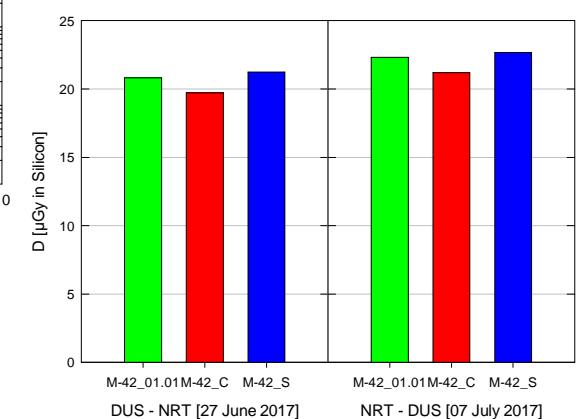
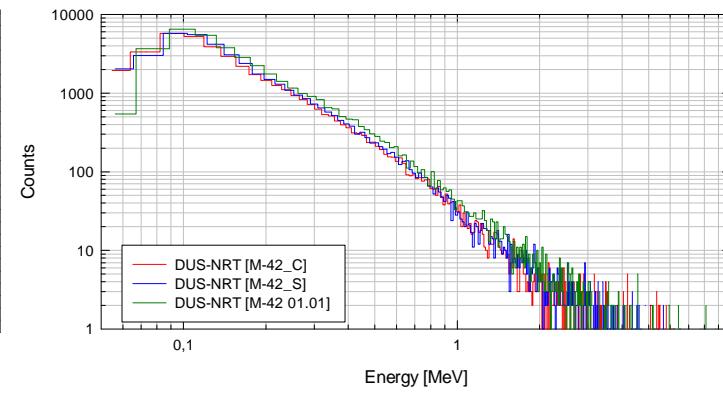
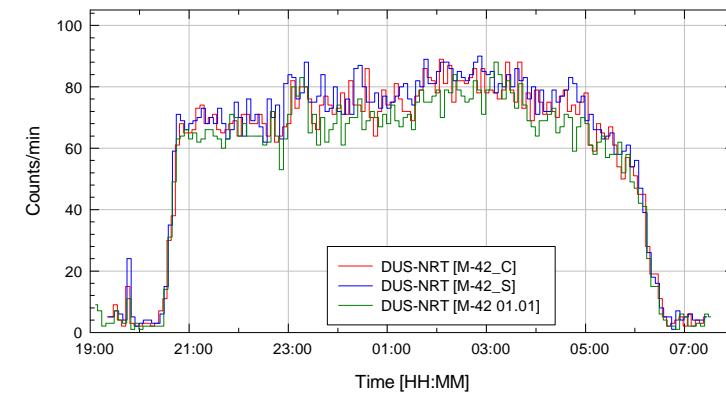
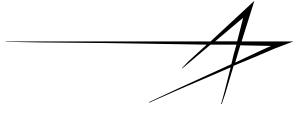


DLR M42 DUS-NRT and return

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DUS-NRT: $20.56 \pm 0.78 \mu\text{Gy}$ in Si
NRT-DUS: $22.07 \pm 0.77 \mu\text{Gy}$ in Si





DLR M42 HIMAC Exposure

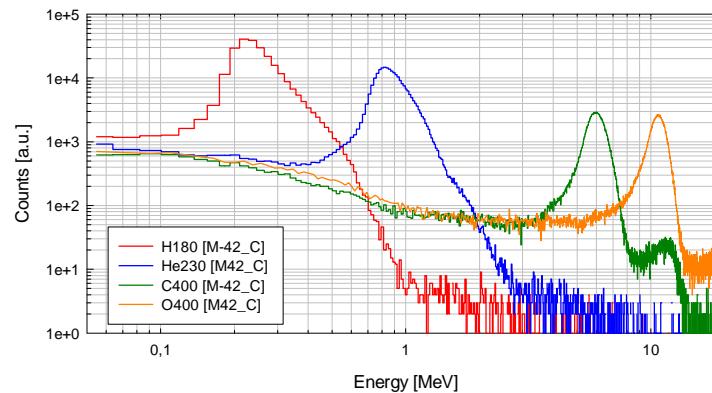
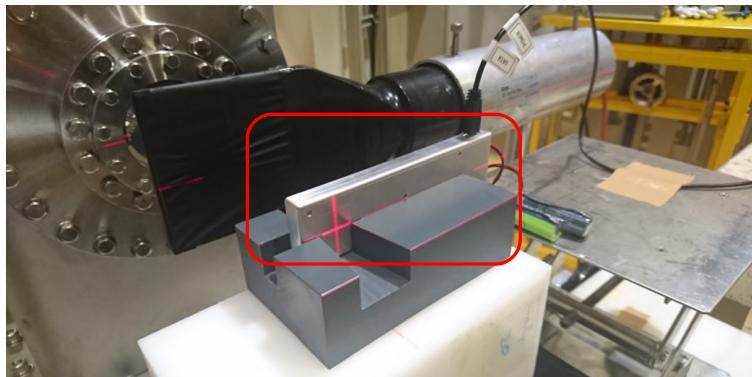
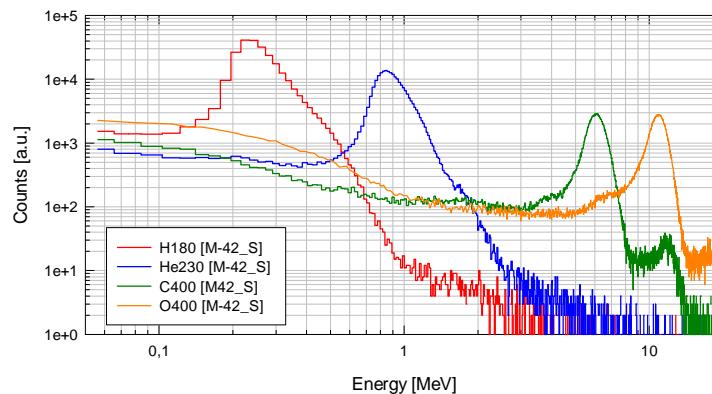
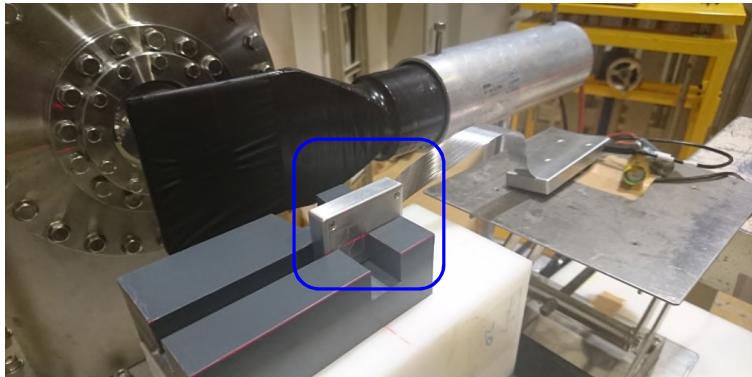


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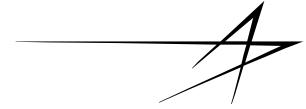
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HIMAC Research Project 17H374





DLR M42 MAPHEUS testing

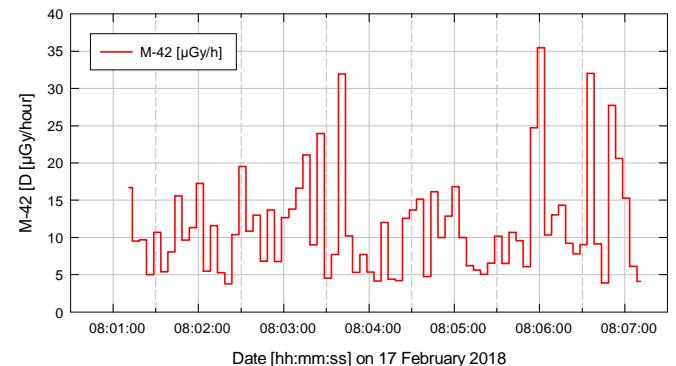
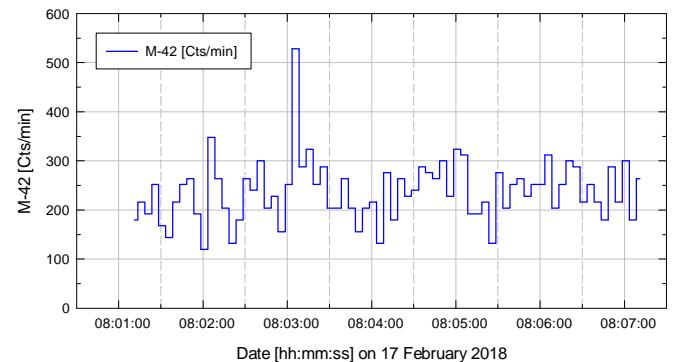


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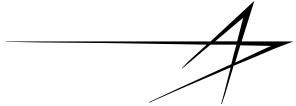
- Load detector test performed aboard MAPHEUS DLR research rocket
 - Max Altitude = 260 km
 - Flight Time = 14 min 10 s (6 min microgravity)
 - Launched from the European Space and Sounding Rocket Range, Kiruna, Sweden (Feb 2018)





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NASA CPAD



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- Crew Personal Active Detector
- ISS Tech Demo currently in progress
- Variable storage rate, no load detector needed
- Direct Ion Storage (Mirion Technologies)
- Mass <35 g, volume = $5.4 \times 3.4 \times 1.8 \text{ cm}^3$
- Battery life >10 months (configuration dependent)
- Display for crew information includes dose rate and cumulative dose
- Additional CPADs to be flown on EM-1 outside of MARE





ESA Active Dosimeter (EAD)



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- **Provided by the European Space Agency**
 - Also referred to as EAD Mobile Unit – Orion (MU-O)
- **Based upon the existing ISS EAD MU**
 - ISS EAD system also includes docking station
 - MU-O requires upgraded battery lifetime
 - Additional instances of the EAD MU-O baselined to fly on Orion EM-1 outside of MARE
- **Mass 150 g, volume 6x10x3 cm³**
- **Thin/Thick Silicon Detector**
- **Instadose®**
- **RadFET**





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DOSIS 3D PDP



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- **Dose Distribution Inside the International Space Station - 3D**

- DLR lead effort to dose map all the ISS segments (2012 – 2018)
- Passive Dosimeter Package (PDP) includes TLDs + OSLDs + CR-39 PNTDs
- Large international participation includes:
 - Technical University Vienna, ATI, Austria
 - Institute of Nuclear Physics, IFJ, Krakow, Poland
 - Centre for Energy Research, MTA EK, Budapest, Hungary
 - Belgian Nuclear Research Center, SCK•CEN, Mol, Belgium
 - Nuclear Physics Institute, NPI, Prague, Czech Republic
 - Oklahoma State University, OSU, Stillwater, USA
 - National Institute of Radiological Sciences, NIRS; Chiba, Japan
 - NASA JSC, Houston, TX, USA



THE HENRYK NIEWODNICZANSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES



SCK•CEN
STUDECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLÉAIRE



Nuclear Physics Institute of the CAS
Public research institution



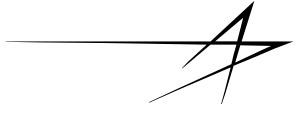


Exploration Mission 1 (EM-1)

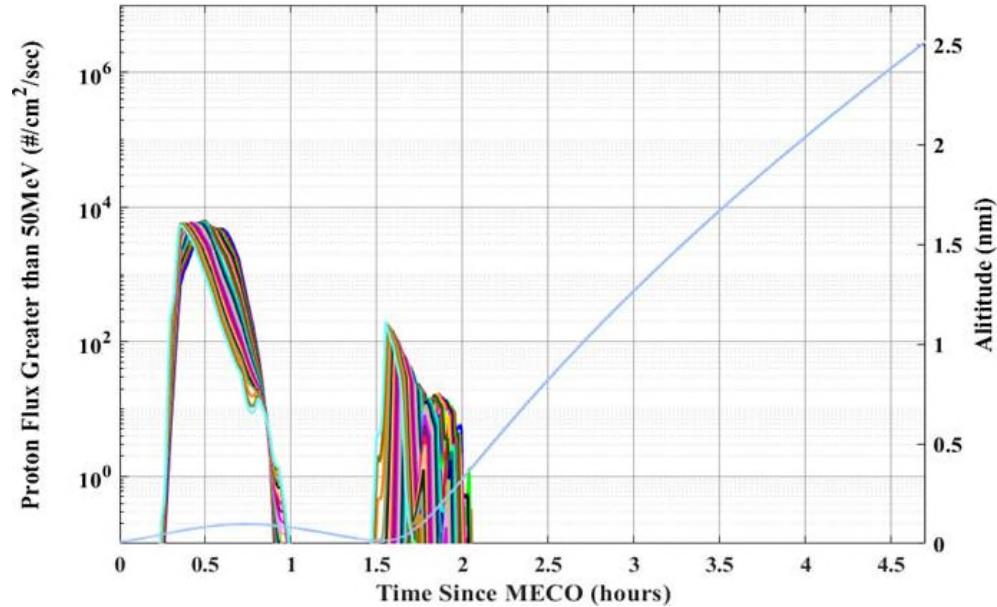
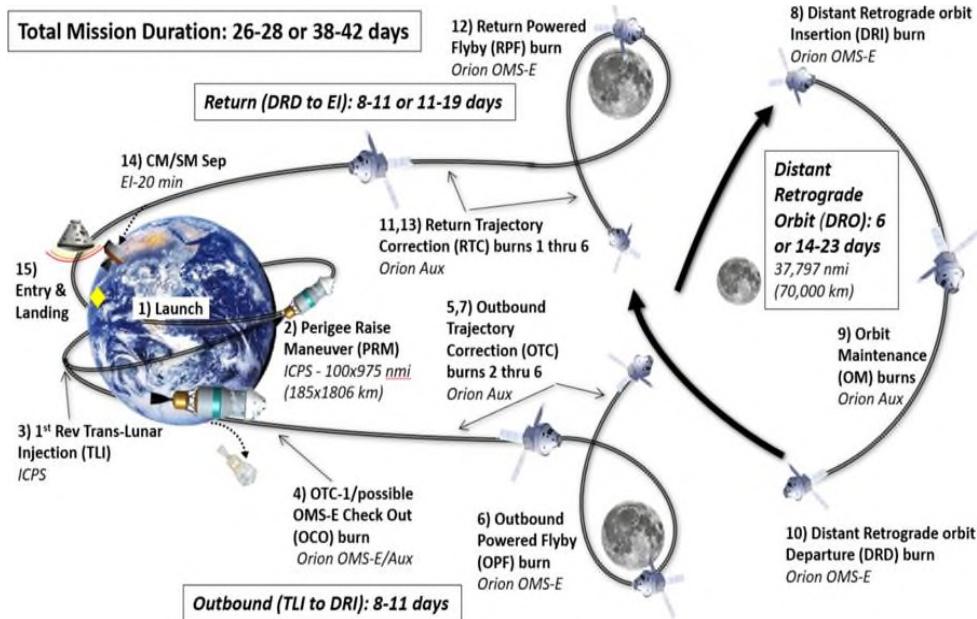
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- First Orion test flight beyond Earth orbit scheduled for 2020
 - Uncrewed flight on Distant Retrograde Lunar Orbit (DRO)
 - Solar minimum: intense GCR, low probability of SPE
 - Van Allen protons useful as SPE surrogate
 - Trajectory through Van Allen belts dependence upon launch date causes ~2x spread in environment (AP-8)





Exploration Mission 1 (EM-1)

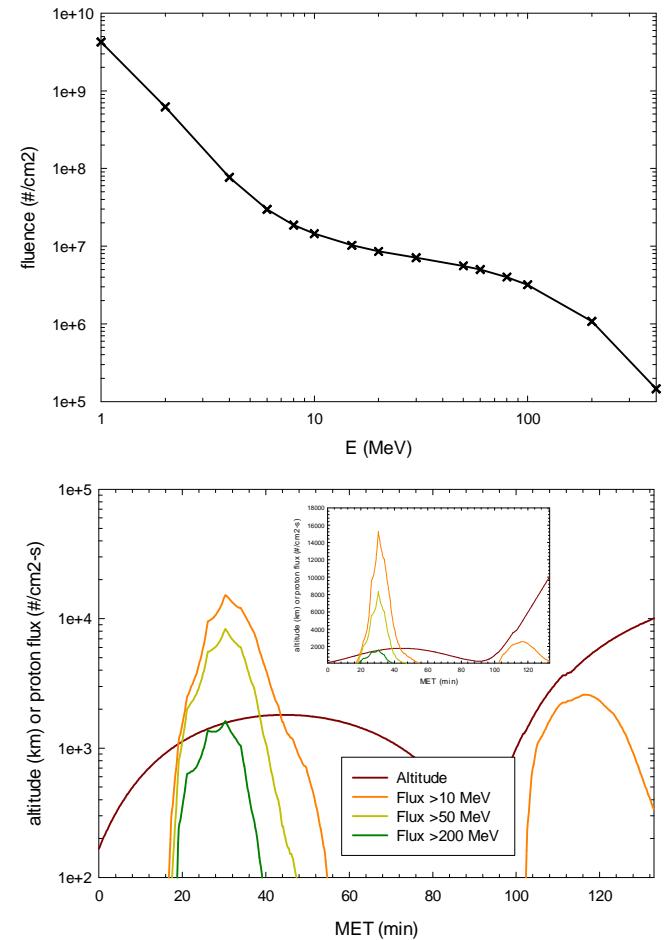
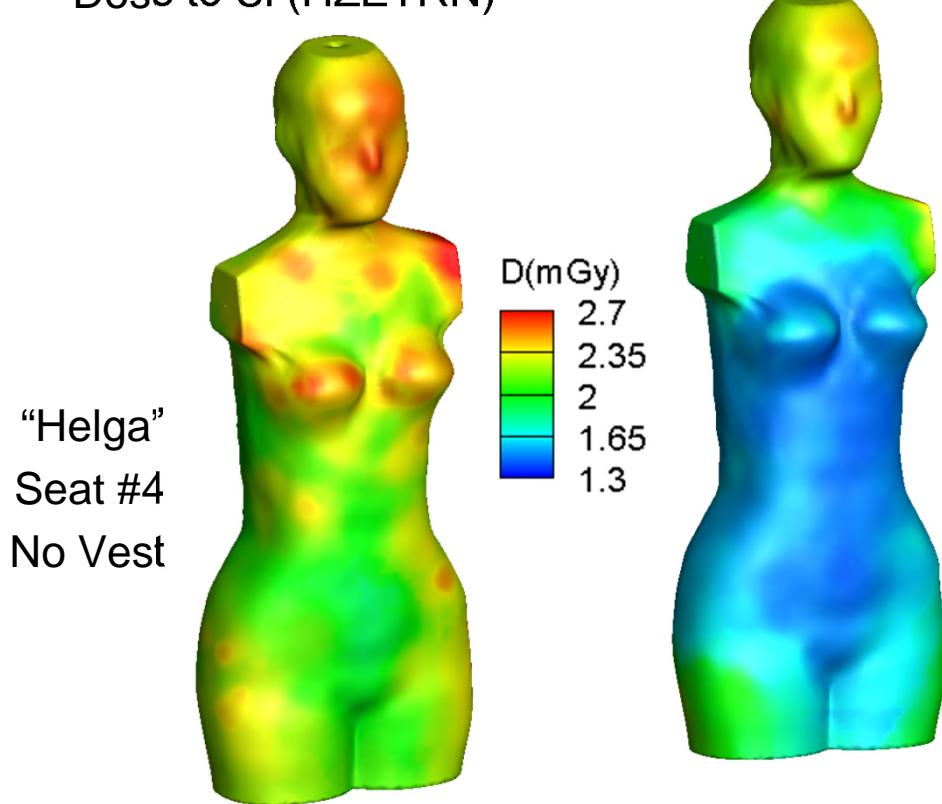
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• Preliminary radiation analysis

- Using MARE and Orion EM-1 CAD models
- Max radiation stressing environment (outbound, AP-8)
- Dose to Si (HZETRN)





Exploration Mission 1 (EM-1)



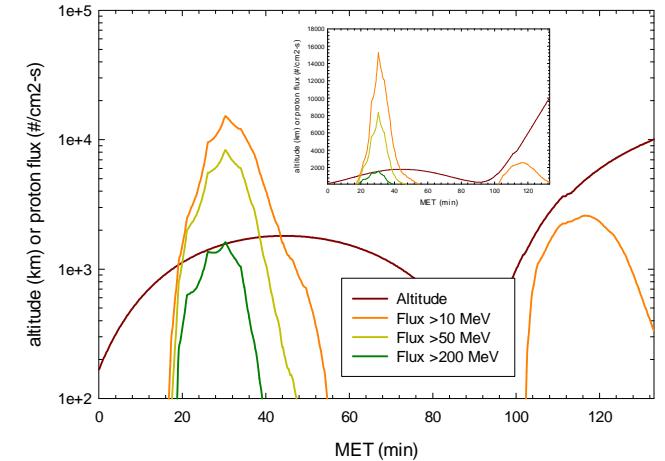
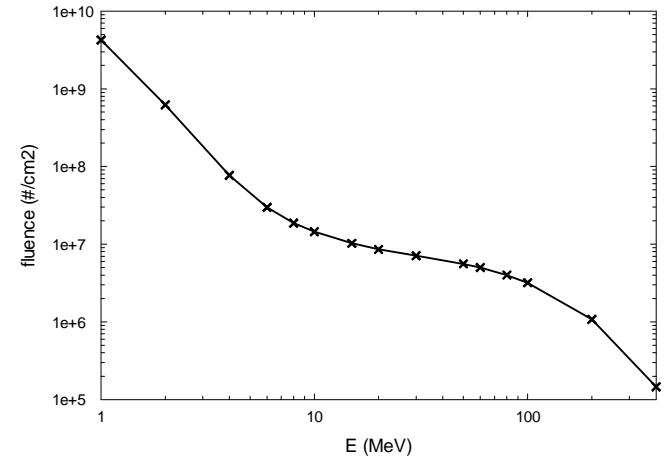
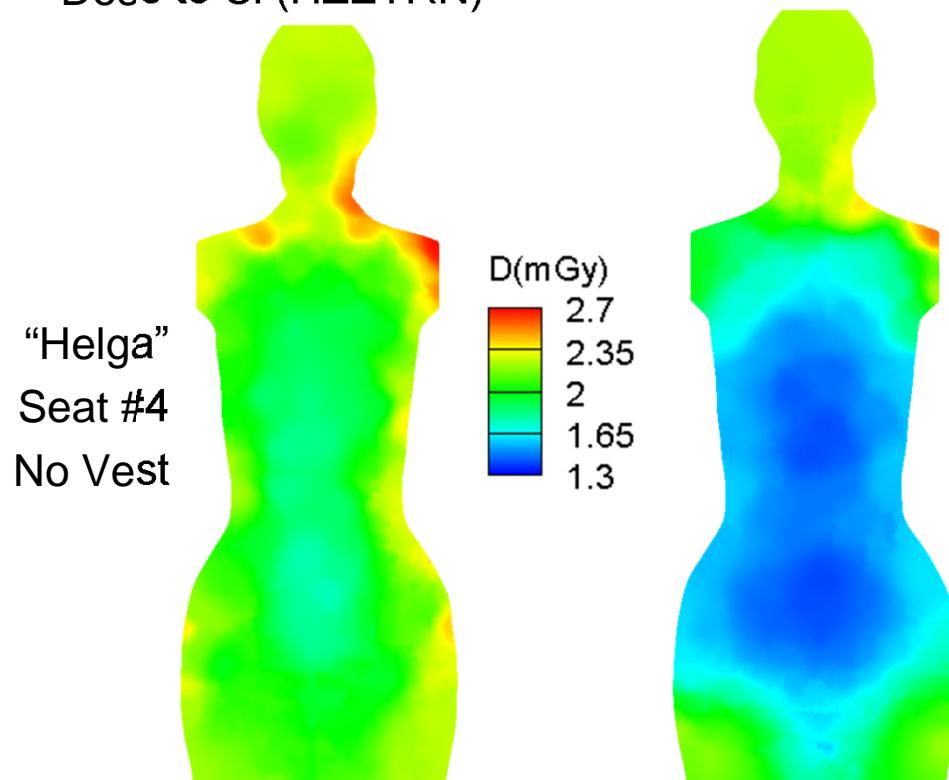
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- Preliminary radiation analysis

- Using MARE and Orion EM-1 CAD models
- Max radiation stressing environment (outbound, AP-8)
- Dose to Si (HZETRN)





Exploration Mission 1 (EM-1)



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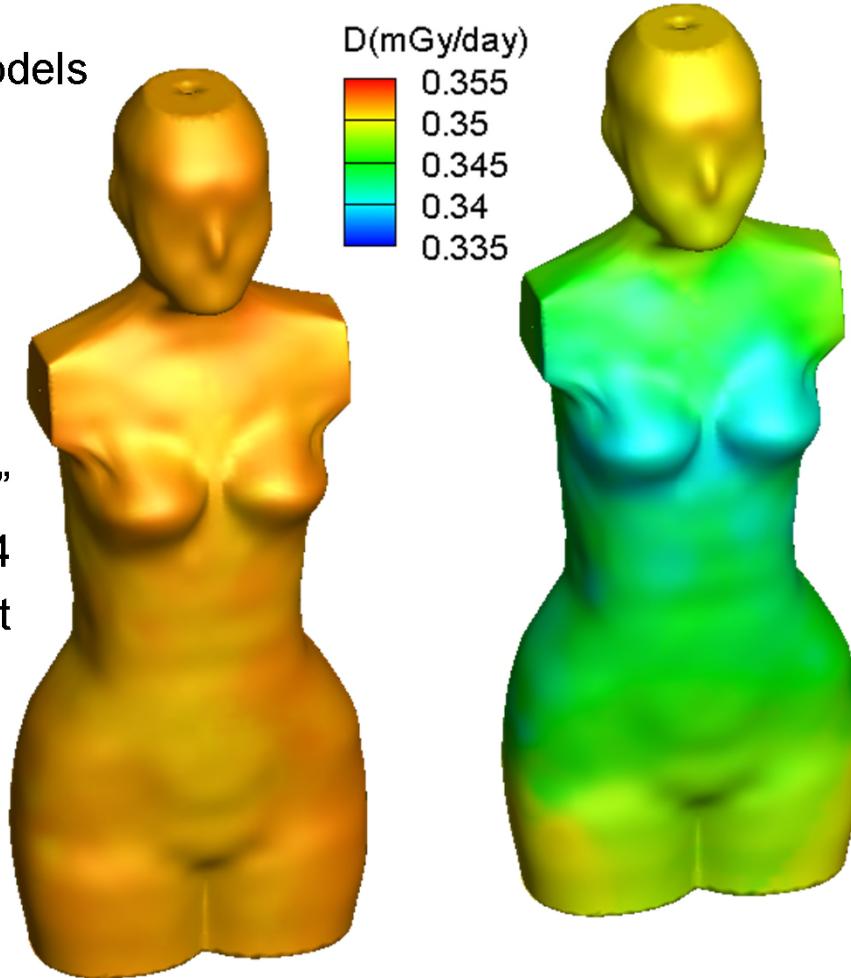
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- Preliminary radiation analysis

- Using MARE and Orion EM-1 CAD models
- GCR Solar Min (Mar 2009)
- Daily dose to Si (HZETRN)

“Helga”
Seat #4
No Vest



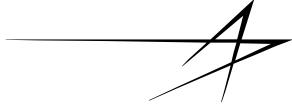
“Zohar”
Seat #3
AstroRad
Vest not shown



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Payload Integration Status

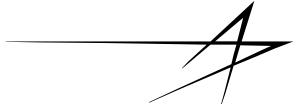
- **Successfully completed combined PDR/CDR (Mar 2019)**
 - Structural analysis, Vibration testing
 - Safety certifications ongoing
- **Installation validation in the Orion Structural Test Article**
 - Mass representative mock-ups
- **Science activities**
 - Additional detectors from HERADO / Hellenic space Agency / Thessaloniki University (Greece)
 - Environment and Dose Projection Refinements
- **Late stow vehicle installation**
- **EM-1 Flight (2020)**
- **Post-flight data processing, consolidation and publication**
 - AstroRad vest improvements



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Conclusion

- Orion is the first Exploration architecture component
 - MARE is among the first Orion payloads
- International collaboration is critical to successful space exploration
- MARE as example of upcoming science research opportunities



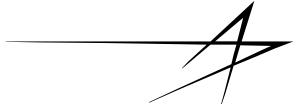


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Backup





Orion Design for Crew Radiation Protection

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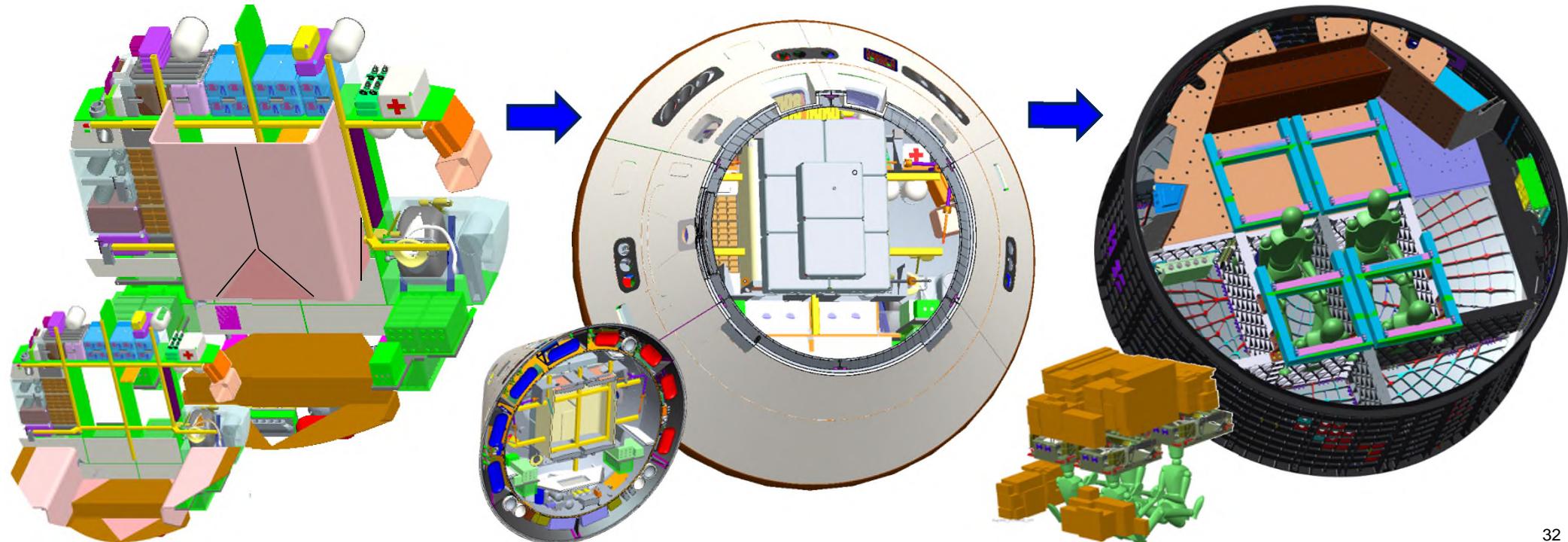
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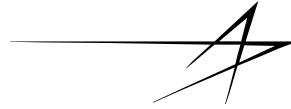
- **Matured throughout the vehicle design**

- Early in the program the Master Equipment List included 254 lbm of Polyethylene radiation shield
- Dedicated shielding mass was progressively reduced and ultimately eliminated
- Current baseline relies on design and operational reconfiguration of cabin in case of SPE





Radiation Shelter Evaluation

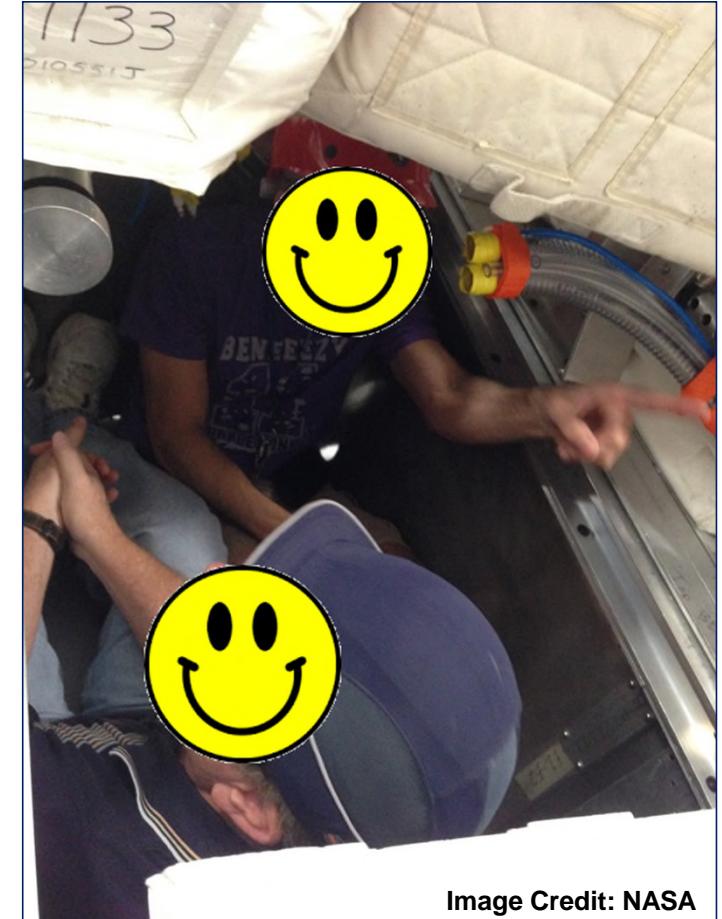


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- 2016 Human In The Loop testing in the NASA JSC Orion med-fidelity mockup



Nominal Cabin Configuration

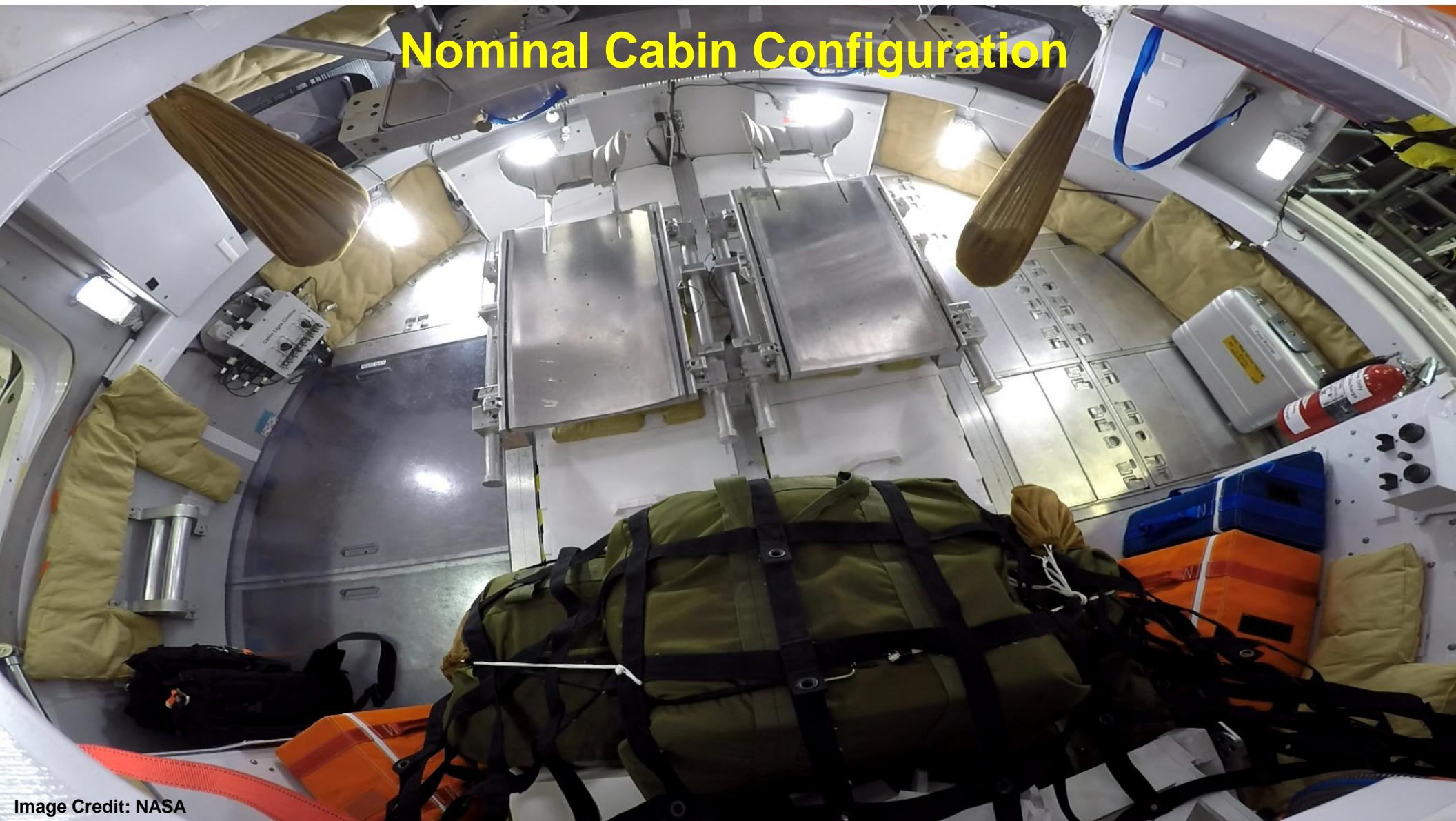


Image Credit: NASA

Cabin Reconfigured for SPE

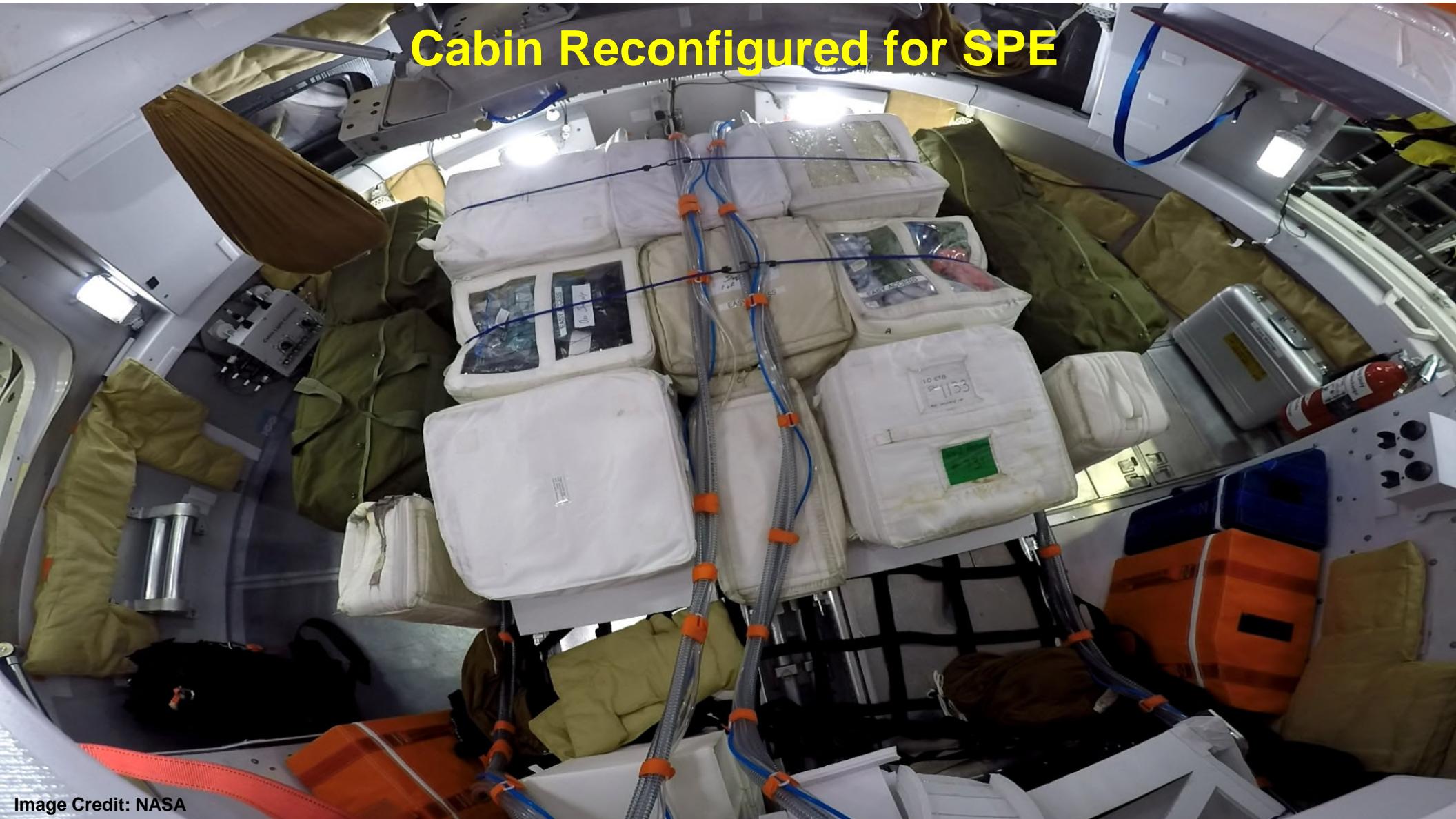


Image Credit: NASA



Radiation Analysis Verification by Measurement



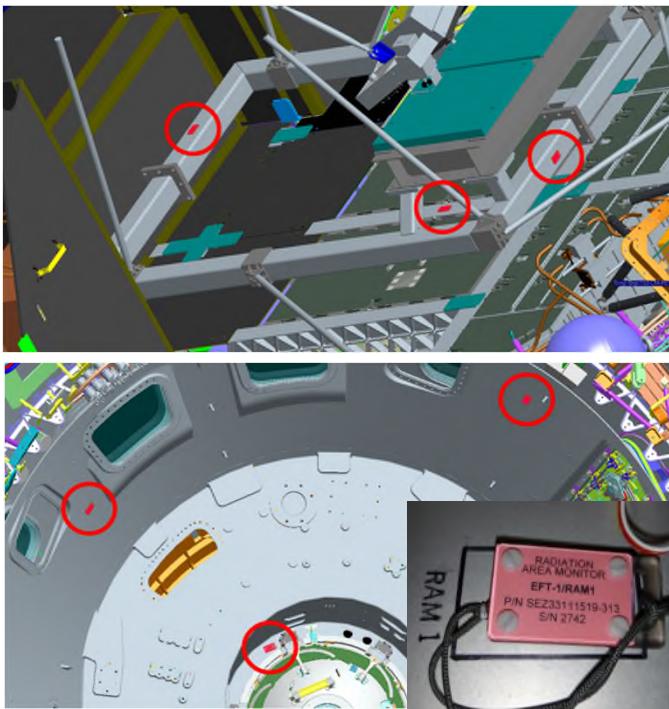
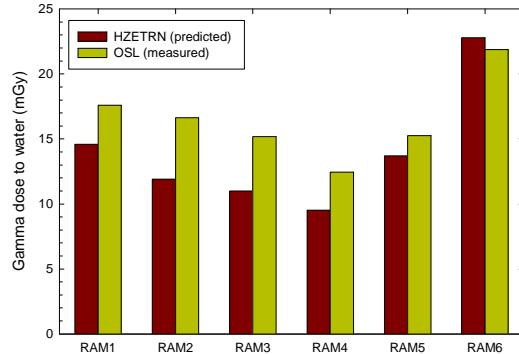
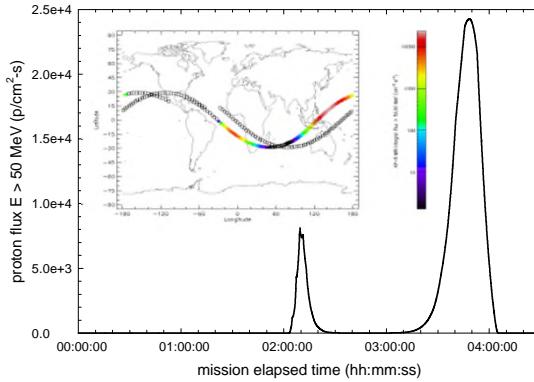
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- **Exploration Flight Test 1 (EFT-1) opportunity to validate radiation analysis**

- High energy re-entry trajectory traversed the core of the Van Allen belts
- Passive (RAMs, OSLDs) and active (BIRD) on-board radiation detectors
- Measurements correlate well with predictions based on planned trajectory and AP-8 model



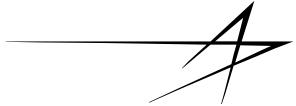
- Dynamic radiation environment
- Radiation transport modeling
- Detector efficiency vs Z/LET
- Body self-shielding
- Internal body dose mapping
- Biological Z/LET susceptibility
- Biological endpoints

**Analysis validation continues
on future flights toward
improved astronaut safety**



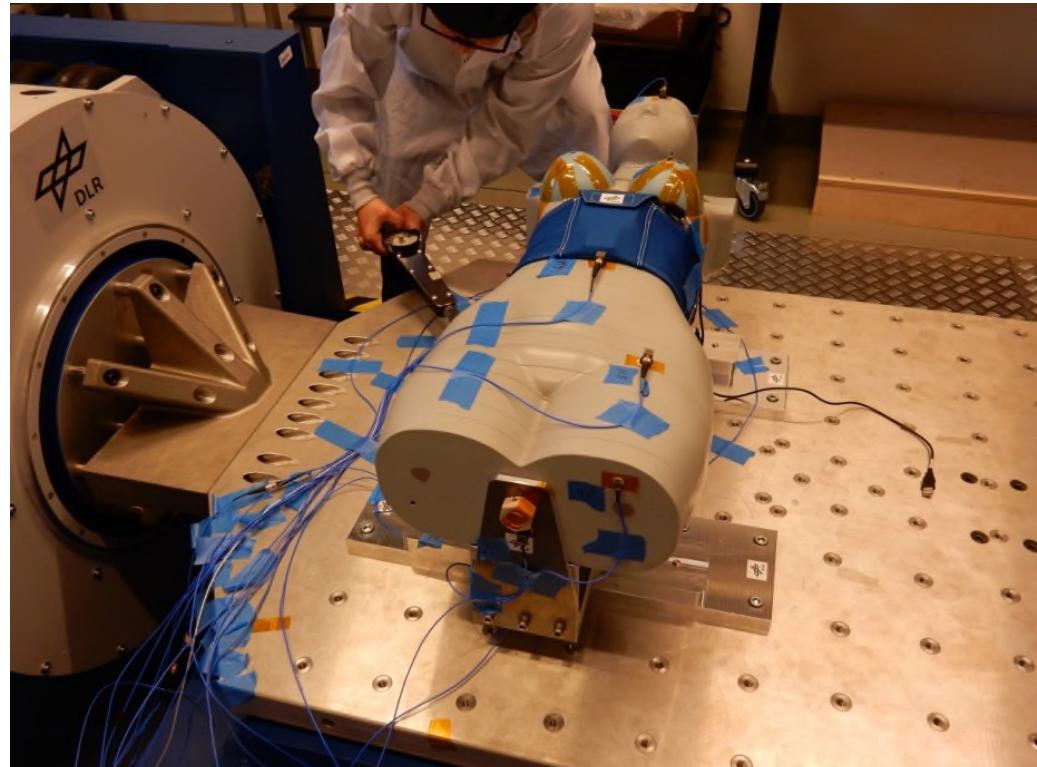
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Vibration Test



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Structural Analysis

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